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# Mine impact burial experiment

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# Mine Impact Burial Prediction Experiment

Peter C. Chu, Timothy B. Smith, and Steven D. Haeger

**Abstract--** Mine Impact Burial Prediction Experiment (MIBEX) was conducted at Monterey Bay on May 23, 2000 using a simulated mine. During the experiment, we carefully observe mine track and mine burial depth while simultaneously taking gravity cores. After analyzing the gravity cores, we obtain the bottom sediment shear strength data set. Such synchronous mine burial depth and shear strength data were used to evaluate the Navy's Impact Burial Prediction Model (IBPM) which creates a two-dimensional time history of a bottom mine as it falls through air, water, and sediment. The output of the model is the predicted burial depth of the mine in the sediment in meters, as well as height, area, and volume protruding. Model input consists of environmental parameters and mine characteristics, as well as parameters describing the mine's release. The MIBEX data show that the current IBPM model needs to be improved.

**Key Words—**Mine impact burial prediction experiment (MIBEX), mine impact burial prediction model (IMPACT25), gravity core, and sediment transport.

## INTRODUCTION

Since the conclusion of the cold war, emphasis has been shifted from blue-water, open ocean battle tactics to littoral warfare. It is in this arena that mine warfare has become an all-important issue. Mine warfare is one of most cost efficient ways to protect critical waterways and inflict serious damage upon a fleet. The fear inflicted upon an enemy fleet after knowledge of the presence of mines is a psychological bonus that enhances their effectiveness as a weapon. Many mines are of the same design as their counterparts from thirty or forty years ago. Their simplicity, effectiveness, and cost efficiency make them an appealing weapon for third world countries.

There are hundreds of variations of mines and they are triggered various ways. In 1776, an American, David Bushnell, who is also recognized as the inventor of America's first submarine, invented the first known sea mine. Bushnell's

mine was a simple watertight wooden keg, loaded with gunpowder, which hung from a float and, at that time, was called a torpedo. In 1777, under orders from General Washington, a number of the kegs were set adrift by Bushnell in an attempt to destroy a fleet of British warships anchored in the Delaware River off Philadelphia. The attempt failed. But the naval mine has since - through the American Civil War, World Wars I and II, and the Korean and Southeast Asian Conflicts - gained a reputation as one of the Navy's least costly, yet most effective, offensive and defensive weapons.

Modern times have not changed the value placed on mines. Although technology has improved and new and more effective mines have been invented, many third world countries still employ mines of the simplest design. Mine detection capability is now in the spotlight.

Mines are deployed one of three ways: Aircraft, sea surface, or subsurface. Mines will float on the surface through inherent buoyancy, float just below the surface using some sort of anchoring mechanism or lodge themselves in the sea bottom. They can detonate by contact, disruption of a magnetic field, or by acoustic detection. For the mines which imbed themselves in the sea floor, the sensitivity of the mine trigger is directly proportional to the amount of the mine protruding from the sea floor. Because of this, it is important to be able to predict the burial depth of the mine depending upon deployment platform, sediment type and oceanographic conditions.

Chu et al. (2000) reviewed the current status of current numerical models for simulating the mine burial process and constituting the viable means for burial depth prediction. These models provided some information for clearing an area of mines. However, the Impact Burial (IB) model was developed to determine the depth at which the mine comes to rest in the sediment upon impact and at which only the momentum equations of the mine gravity center is considered (Arnone and Bowen, 1980). The IB model was designed to create a two-dimensional time history of a cylindrical mine as it falls through air, water, and sediment phases (Figure 1). The burial depth of the mine in the marine sediment is then calculated from the mine's velocity on contact with the sediment and the sediment characteristics. Several revisions have been made to the model to refine the physics and allow for more realistic geometry and more extensive input from the user. Most notable are the changes made by Satkowiak (1987) and Hurst (1991). Other revisions involved translating to newer computer language. Currently, the model allows the

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user to input nearly any value for each environmental parameter.

The most popular IB model is IMPACT25. The altitude from which the mine is released determines the velocity and attitude of the mine as it reaches the air-water interface. IMPACT25 simulates one of the two kinds of mine motion: (1) falling downward without any rotation around its gravity center, and (2) “tumbling” with a constant rate of rotation. The attitude of the mine upon reaching the water is impacted greatly by the release altitude. Although not accounted for in the model, this rotation rate may be caused or affected by wind.

In the water phase, this rotation rate is damped significantly. However, it still has a great effect on the angle the mine makes with the sediment upon impact. Currents may affect the rotation rate in the model, but again are not accounted for in the model. The water depth only has an effect on impact velocity if it is less than that required for the mine to reach terminal velocity, the velocity at which the deceleration due to frictional drag is equal to the acceleration from gravity. The velocity at which this equilibrium is reached is a function of the weight of the mine. Since mines are laid in shipping channels almost exclusively, one may assume that water depths in excess of that required for a mine to reach terminal velocity are the norm. Water temperature has an effect on the viscosity of seawater, and hence increases the drag of the seawater on the mine.

Data input for the IMPACT25 model can be split into two categories. The first category is rudimentary deployment and oceanographic water column data. The second category is more detailed sediment data. Penetration depth predictability is going to depend directly on impact velocity, and sediment density and shear strength values. The model puts sufficient emphasis in the utilization of sediment parameters but idealistic conditions for predicting impact velocity.

The output of the model is in question due the instability of ocean sediment. Until this experiment was conducted, dated sediment values were used when running the code that led to skepticism in the validity of its output. Changes in the water column due to turbulence and currents above an impact area have a significant effect on sediment characteristics in the upper layers. These same changes in the water column have a direct effect on the impact velocity and orientation and are not addressed by the model. Sensitivity studies (Taber 1999; Chu et al. 2000) indicate the importance of the environment; especially on the bottom shear strength in the mine impact burial.

Before transferring the IMPACT25 model for naval operation use, we should verify the model using synchronous mine impact burial and environmental data. Unfortunately, it is very hard to find such a data set. The current data sets are either the mine data or the environmental data only. It is therefore a high priority to collect the data for the evaluation of the IMPACT25 model.

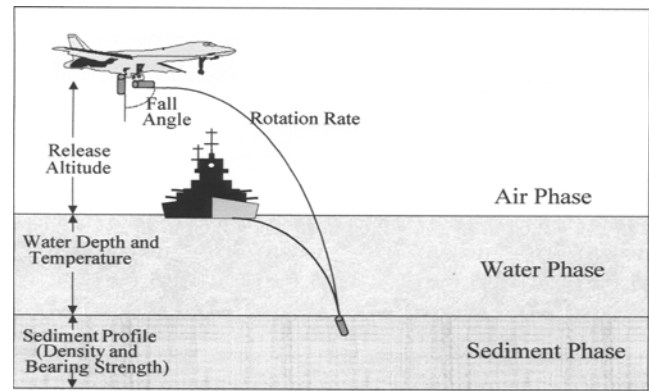


Fig. 1. The trajectory of a cylindrical mine as it falls through three phases: air, water, and sediment. Labels are parameters used by the model to calculate the velocity, attitude, and burial depth of the mine.

This study includes three parts: (1) collecting synchronous mine impact burial and environmental data through the Mine Impact Burial Experiment (MIBEX) at Monterey Bay, (2) analyzing the real-time environmental data collected at the Rapid environmental Assessment Laboratory (REAL), and (3) evaluating IMPACT25 using the MIBEX data.

## I. ENVIRONMENT OF THE MONTEREY BAY

### A. Geology and Structure

The experiment was conducted in the Monterey Bay National Marine Sanctuary (MBNMS) off the central coast of California. The location was chosen because of its accessibility and the oceanographic data collection capability already in place. The MBNMS spans nearly 10,000 km<sup>2</sup> in the central California region, and extends offshore an average distance of approximately 50 km (a maximum distance of nearly 100 km in the Monterey Bay area and a minimum distance of 15 km off Partington Point) between the Farallon Islands in the north and Morro Bay in the south (Figure 2).

It contains one of the world's most geologically diverse and complex seafloors and continental margins. The MBNMS is located on a plate boundary, which separates the North American Plate from the Pacific Plate, and is marked by the San Andreas fault system. This is an active tectonic region with common occurrences of earthquakes, submarine landslides, turbidity currents, flood discharges and coastal erosion. It is also a region of extensive natural and economic resources.

Coastal topography varies greatly, encompassing steep bluffs with flat-topped terraces and pocket beaches to the north; large sandy beaches bordered by cliff and large dune fields mid-sanctuary; and predominately steep, rocky cliffs to the south. Low- to high-relief mountain ranges and broad, flat-floored valleys are prevalent farther inland.

The Santa Cruz and Gabilan mountain ranges dominate the topography in the northern and central half of the region. Two major rivers (San Lorenzo and Pajaro Rivers) and a major creek (Scott Creek) enter Monterey Bay from these highlands

through well-defined valleys (Figure 2). Elkhorn Slough, an old river estuary that today is occupied only by tidal salt marshes, extends inland from Moss Landing for more than 10 km. The broad, extensive Salinas Valley and the northern Santa Lucia Range are the dominant topographic features in the southern half of the region; the Salinas River is the major drainage system (Figure 2). South of Monterey, the west flank of the Santa Lucia Range drops abruptly into the ocean. Here, the valleys of the Carmel and Little Sur Rivers are dominant topographic features. From Point Sur to Morro Bay many streams and creeks drain the southern Santa Lucias and cut the steep western face of the mountain range.

The MBNMS is located along the active transform boundary (the San Andreas fault system) separating the Pacific Plate from the North American Plate. Here the fault system is over 100 km wide and incorporates faults in the offshore, including those of the Palo Colorado-San Gregorio and Monterey Bay fault zones. These fault zones are seismically active, and in many places offset the seafloor or Quaternary sedimentary rocks. A paleo-subduction zone occurs along the MBNMS western boundary; the fossil thrust faults in this zone appear to control the structure at the base of the continental slope. Most of the northern and central parts of the MBNMS lie within the Salinian block. It is composed of allochthonous (i.e. transported to local region) Cretaceous granitic basement material, primarily overlain with Neogene marine sedimentary units; it has been tectonically slivered into its present position. This block has been carried upon the Pacific Plate as the plate moves northward, slipping along the San Andreas fault for about the last twenty-one million years.

In the Monterey Bay region, the plate boundary between the North American and Pacific plates is comprised of the San Andreas fault system, consisting of the Hayward-Calaveras and San Andreas fault zones on land, and the offshore Palo Colorado-San Gregorio fault zones. The Palo Colorado-San Gregorio is the major active fault zone within the MBNMS. It is a right-lateral strike-slip fault zone oriented generally north-south, comprised of two or more parallel and fairly continuous fault segments that extend at least 100 km from Point Año Nuevo in the north to Garrapata Beach (10 km north of Point Sur). The amount of right-lateral offset along this fault zone has been measured by different methods and at several locations; offset varies from 80-90 km to as much as 150 km.

The Monterey Bay fault zone is a wide (~10 km), echelon (i.e. composed of short, discontinuous, offset, roughly parallel faults) formation comprised of many fault segments ranging from 5 km or less up to 15 km in length. The Monterey Bay fault zone is either truncated or merges with the San Gregorio fault segment of the Palo Colorado-San Gregorio fault zone.

Monterey Canyon, the most dramatic submarine feature of the sanctuary, rivals the Grand Canyon in relief and topographic complexity. Monterey Canyon ranks among the larger canyons of the world and has a richness of life that exceeds that of most land and marine areas. The marine

sanctuary, about 7,500 square kilometers of ocean and seafloor off central California, is home to a rich diversity of marine life. More than 30 species of marine mammals live in or visit the Bay, making it one of the largest collections in the northern hemisphere. For example, Bairds Beaked Whale navigates the canyon to make infrequent surface visits to the Bay. The sanctuary is rich in marine life because nutrient-enriched seawater upwells along the steep margin from deeper, colder waters.

Sediments derived from land accumulate in the marine environment, often at a temporary location awaiting a large storm, strong currents, or a quick shake from an earthquake to send them cascading down the canyon. The region is tectonically active, a fact underscored by the 7.0-magnitude Loma Prieta earthquake in 1989. Much has been learned from that event, including indications that the style of faulting may be significantly different than previously thought. Such differences have implications for how rocks move and react to shock waves, which, in turn, influence the size of earthquakes. Further studies are needed to determine how these rocks are packaged, how the packages move, and what effect that movement has on the seafloor and adjacent coast. Sediments deposited on the shelf are affected by winter storms, which resuspend particles and transport them to new locations. For example, giant landslides and currents of turbid materials occur in Monterey Canyon when waves or earthquakes destabilize huge piles of sediment at the head of the canyon. These slides and flows are well documented, but the extent of movement is not well known. Recent mass movements of sediments have moved electronic instruments on the seafloor miles down the canyon. Movement of sediments along the coast and their ultimate accumulation more than 300 kilometers from the shore are topics of study requiring a long-term research commitment.

### *B. Oceanography*

MBNMS including Monterey Bay and the coastal area between the Gulf of the Farallones and Point Piedras Blancas, is closely tied to processes of the California Current. The California Current is an eastern boundary current that has been characterized generally as a broad, shallow, slow southward moving current exhibiting high spatial and temporal variability. The California Current is the eastward portion of the clockwise North Pacific Gyre and transports low salinity, cool water equatorward. Associated with the coastal surface flow is a poleward undercurrent, the California Undercurrent. Even though the California Current is one of the most-studied oceanographic features in the oceans, it is difficult to predict at any particular instant the location of its velocity core, its speed, or direction. Indeed, at various locations observers might characterize the current as south flowing (as it often is in offshore regions), westward flowing (as is frequently observed in a coastal jet near Point Reyes), or eastward flowing (as found in the southern regions of such jets). At times, principally in winter, the nearshore current flows northward.

The California Current can be divided into three regions (based on the seasonal amplitude variation and standard deviation of dynamic height): an offshore oceanic regime, a coastal regime and an intervening transition zone. This transition zone lies approximately 200-300 km west of Point Sur. Geostrophic speeds in the core of the California Current may approach 25 cm/s, but generally are 5 to 10 cm/s (0.1 to 0.2 knots). The core of the California Current lies in the salinity minimum about 300 km offshore of Point Sur, within the transition zone, and is not associated generally with a thermal gradient.

The California Current is richly populated with semi-stationary jets and eddies. The importance of these features, which represent the highly variable oceanographic "weather" of the California Current, lies in their offshore transport of cool, nutrient-rich upwelled water. This extends the effects of nearshore upwelling which is confined to a band about 50 km wide to several hundred km. Cross-shore velocities may reach 1 m/s which is an order of magnitude greater than characteristic speeds of the California Current core. In what are called "squirts," the flow may be directed offshore, and where the "squirt" dissipates elongated "hammerhead" features evolve. Between mesoscale eddies, the flow is directed offshore north of cyclonic eddies and onshore south of them. A jet may be found off Point Sur that transports cool, upwelled waters offshore 100 km. The "San Francisco Eddy" is a semi-permanent cyclonic eddy northwest of Monterey Bay, while other observations describe anti-cyclonic eddies in this region. Current meter measurements and estimated geostrophic flow in an anti-cyclonic eddy southeast of Monterey Bay. Between that eddy and a cyclonic eddy just north of it strong onshore geostrophic flow was observed.

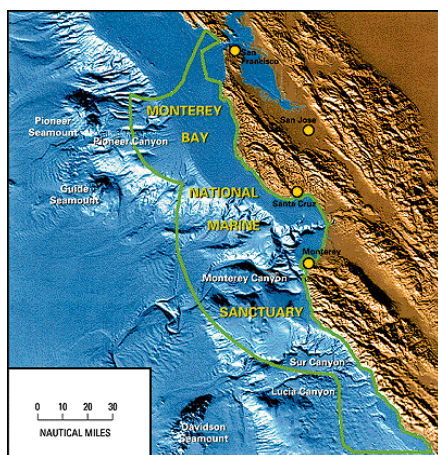


Fig. 2. The Monterey Bay National Marine Sanctuary.

## 2. MIBEX AT THE MONTEREY BAY

### A. Experiment Preparation

A major purpose of MIBEX is to collect synchronized environmental and mine burial data. To accomplish this, the Monterey Inner Shelf Observatory (MISO) at the Naval Postgraduate School (NPS) off of Del Monte Beach in Monterey Bay was selected to provide the ocean environmental data such as waves and currents. After an exploratory dive near MISO, the bottom was found to be composed of "sandy ledges" and the water depth was approximately 12 meters (similar to real world bottom mining environments). Jon Heine was contacted and solicited to be the dive supervisor for the experiment. It was ascertained that a minimum of four divers would be needed to safely go up and down the 12-meter depth 20 times. Heine's divers would also take the gravity cores and film the barrel entry and other pertinent underwater evolutions.

The next task was contacting the United States Geological Survey (USGS) office to determine the proper procedure for taking and analyzing gravity cores. Dr. Homa Lee volunteered to provide assistance on May 31, 2000 and offered the use of the USGS freezer to store the gravity cores after the experiment. Prior to this happening, gravity cores had to be fashioned. 2 ½ inch polycarbonate piping and rubber stoppers were ordered. The polycarbonate piping was cut into eight, three-foot lengths and four, two-foot lengths. These were carried in a special rack designed to transport the sediment intact to the USGS.

On the afternoon of May 22, 2000, the R/V John Martin was loaded with the mine, gravity cores and dive equipment. Captain Lee Bradford supplied a seaforth quick-release to be used when dropping the barrel. This quick release could be easily fastened and released by a diver in the water, therefore providing the greatest margin of safety for the divers. On the morning of May 22, 2000, Andy Andersen of the Oceanography department at NPS, contacted the Environmental Health office and secured a 55 gallon drum (Figure 3) which was to be modeled as the "mine." Although "ribbed," it was assumed the symmetrical design would have little effect on hydrodynamics in the water column.



Fig. 3. The model mine.



### B. Experiment

On May 23, 2000, the R/V John Martin got underway at 0630. The team was on location and in the water by 0805. After an extensive safety discussion, it was decided that the barrel/mine would be released while touching the surface. This would be to eliminate any chance of inertial effects caused by uneven introduction into the air-sea interface. This also set the initial velocity parameter in the code to zero.

The barrel was to be released 20 times, although, only seventeen drops were actually made because of diver limitations. The diver would snap the quick-release shackle on the barrel and then dive down to conduct measurements. The average depth of the water was 13 meters. Since it was uncertain the path the barrel would follow, both the releasing diver and a second safety diver would stay on the surface until after the barrel had dropped. Once reaching the bottom, one diver would take penetration measurements using a meter stick marked at millimeter increments while the other would take a gravity core.

After 17 drops, the divers began to run out of air and results were not varying greatly so the decision was made to end the experiment. Upon return to the Monterey Bay Aquarium Research Institute, the gravity cores were taken immediately to the USGS Laboratories in Menlo Park, California where they were refrigerated until the analysis could be performed on May 31 – June 1, 2000.

## 3. SEDIMENT DATA ANALYSIS

### A. Gravity Core Analysis

Analysis of the gravity cores was begun on May 31, 2000 at the USGS Laboratories in Menlo Park, California with the aid of a graduate student, Priscilla Barnes. The gravity cores were sliced into two-centimeter segments to a depth of ten centimeters, and then sliced into four-centimeter segments. A Fall Cone Apparatus (Model G-200) was used to determine sediment shear strength.

In the test, it is assumed that the shear strength of sediment at constant penetration of a cone is directly proportional to the weight of the cone and the relation between undrained shear strength  $s$  and the penetration  $h$  of a cone of weight  $Q$  is given by:

$$s = KQ / h^2$$

where  $K$  is a constant which depends mainly on the angle of the cone, but is also influenced by the sensitivity of the clay/sediment. Four different cones are used with this instrument, each one having the measuring range listed in Table 1. The cones are suspended from a permanent magnet. By pressing a knob, the magnet is moved so that the magnetic field is broken momentarily, and the cone is released. Measurements are taken of penetration depth and the evolution is repeated five times per sediment slice. These values are then averaged and correlated with a table which gives shear strength.

TABLE 1 MEASURING RANGES OF THE GRAVITY CORES

WEIGHT (g)	Apex- Angle	Penetration n (mm)	Undrained shear strength (kPa)
400	30°	4.0 – 15.0	25 – 1.8
100	30°	5.0 – 15.0	4 – 0.45
60	60°	5.0 – 15.0	0.6 – 0.067
10	60°	5.0 – 20.0	0.10– 0.0063

### B. Sediment Profiles

Previous studies (Taber 1999; Chu et al. 2000a,b) showed that the sediment parameters are the most critical element in determining how deep the mine was buried when it came to rest. Sensitivity to the alteration of sediment density and shear strength was tested using six sediment profiles including three profiles from Sydney Harbor (Mulhearn, 1993) and three profiles available for selection in the IB model. The profiles included in the model are called simply “softsed”, “medsed”, and “hardsed” and do not clearly correspond to specific sediment types.

During the MIBEX at the Monterey Bay, we obtained 17 gravity cores. Sediment density was observed to generally increase until approximately 6-9 cm below the surface after which it would decrease (Figure 4). Sediment shear strength tended to increase as depth increased (Figure 5).

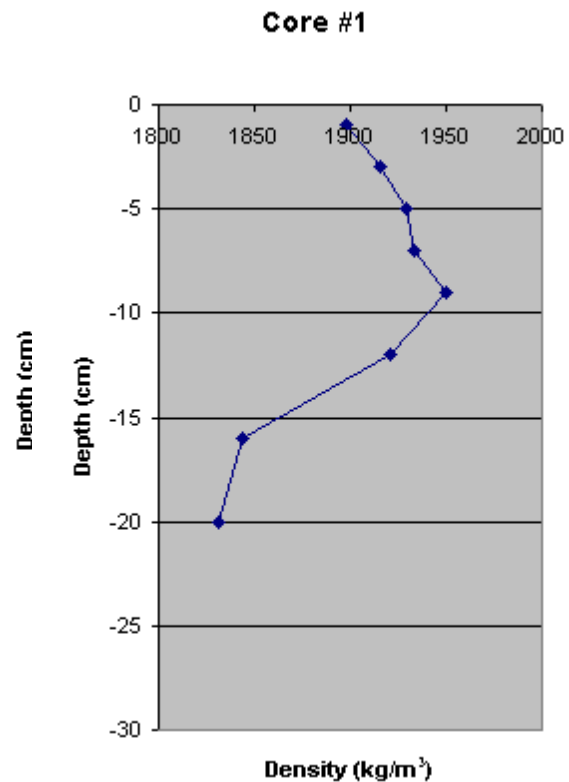


Fig. 4 Sediment density profile at the gravity core #1.

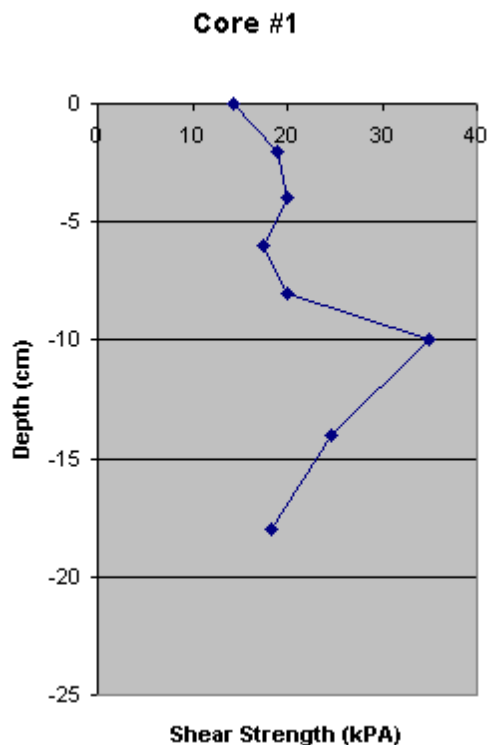


Fig. 5 Sediment shear strength profile at the gravity core #1.

#### C. Sediment Density-Shear Strength Relation

Hayter (1986) discussed an equation originally derived by Krone (1963) for deriving shear strength,  $S_u$ , from density using empirically derived coefficients  $\alpha$  and  $\beta$ :

$$S_u = \alpha \rho^\beta \quad (2)$$

Values for  $\alpha$  and  $\beta$  must be calculated for each separate sediment type, after which the shear strength can simply be calculated using the coefficients. The scatter diagram between shear strength and density (Figure 6) doesn't show such an exponential relationship. However, it does indicate that the higher the density, the higher the shear strength.

### 4. REAL/MISO DATA ANALYSIS

#### A. General Information of REAL/MISO

The Monterey Inner Shelf Observatory (MISO) is a component of the Rapid Environmental Assessment Laboratory (REAL) being developed by the oceanography and meteorology departments at NPS (Figure 7). The REAL laboratory encompasses a range of littoral oceanography observation and modeling programs focused on littoral (coastal) oceanography. MISO, designed and implemented by Research Associate Professor Tim Stanton, has a long term cabled instrument frame deployed at the southern end of Monterey Bay in 12m of water, about 600m from the shoreline, with support instruments on the sand dunes inshore from the underwater frame. The instruments on the 12m frame are designed to study the interaction of winds, waves and the sediment bed in the inner continental shelf, just offshore from

the surf zone. Surface observations of the surf zone and breaking waves are made from an automated digital camera located on the sand dune overlooking the underwater frame. By using a high bandwidth multifiber optic and power cable connected to a shore terminus, long term measurements of these important coastal processes can be made for use in research programs and teaching by faculty of the Oceanography Department at NPS and shared with other users. Hourly summaries of the data sets are available through the main MISO web site. An offshore directional wave buoy deployed in January 2000 provides hourly updated directional wave spectra and wave height / direction time series.

#### B. Real-Time Wave Data

Analysis of wave height data provided by the MISO experiment shows a significant wave motion of approximately 0.5 meters (Figure 8). Oscillation of wave heights significantly affects water depth and subsequently terminal velocity of the mine upon impact. This is especially significant when running the model in shallow depths.

Although not a parameter considered in the IB model, wave action has a direct effect on water depth and, therefore, on velocity of the mine as it reaches the sediment interface (Taber 1999). This effect only becomes significant when the ratio of water depth to wave height is high, and only at very low release altitudes.

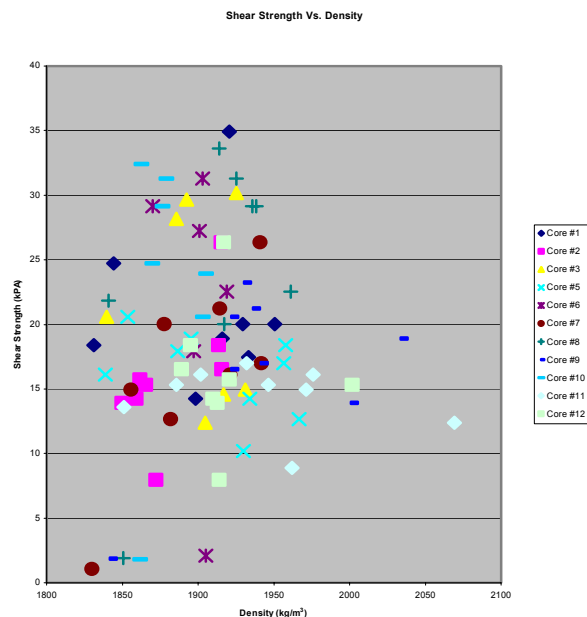


Fig. 6. Shear strength versus density near MISO at Del Monte beach of the Monterey Bay.

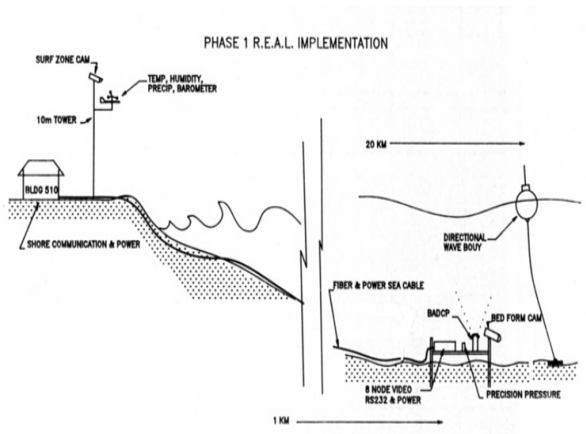


Fig. 7. REAL phase-1 implementation.

## 5. MINE IMPACT BURIAL

### A. Hydrodynamic Processes

IMPACT25 tries to estimate the characteristics of the water column by using fluid drag approximations in its calculations. The essential elements of the mine impact burial model translate into the science and engineering of hydrodynamic process of a falling object and of sediment transport. The current model is only based on the momentum balance of the falling mine,

$$\int \frac{dV}{dt} dm = F_{w,a} + F_b + F_d \quad (3)$$

where  $V$  is the velocity of the mine,  $F_{w,a}$  is the force due to the air weight of the mine,  $F_b$  is buoyancy force and  $F_d$  is drag force.

Buoyancy force is the upward force exerted upon a mine in the gravitational field by virtue of the density difference between the mine and that of the surrounding fluid. We use the Cartesian coordinate system  $(x, y, z)$  with the  $z$ -axis in the vertical direction, and use the unit vector  $k$  along the  $z$ -axis (pointing downward). The buoyancy force is then computed using the density value for air or water,  $\rho$ :

$$F_b = -\rho g C k \quad (4)$$

A cylindrical mine penetrating into water passes through two distinct regimes. The first regime is the cavity regime. As the mine pushes into the air-water interface, it creates a cavity that consists of a combination of air and water particles. The ratio of air to water in the cavity decreases until the fluid properties become that of water only, at which time the mine is in the fully wetted regime. A temporal variation of the mine's vertical position can be calculated (Taber 1999; Chu et al. 2000). When the vertical distance of the mine traveling in the water equals the water depth, the mine velocity is called the bottom impact velocity, which is the initial condition for determining the mine burial depth in the sediment.

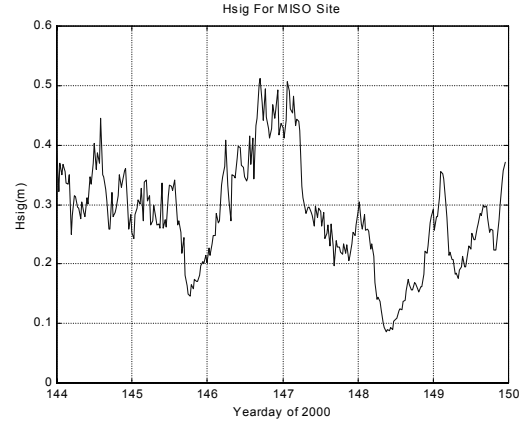


Fig. 8. Significant wave height during MIBEX.

Penetration of the cylindrical mine into the bottom sediment depends primarily on the attitude and velocity of the mine upon impact, as well as the sediment properties of density and shear strength. Initial impact of the cylindrical mine into the sediment creates a cavity in which the fluid properties of water and sediment are interacting. The kinetic viscosity of the sediment,  $\Lambda_s$ , is not a pure constant, but rather is equal to the water viscosity,  $\Lambda_w$ , plus that resulting from the shear stress of the sediment:

$$\Lambda_s = \Lambda_w + S_u / (\Delta_s dV/dz) \quad (5)$$

where  $\Delta_s$  is the density of the sediment and  $S_u$  is the shear strength.

### B. Mine Burial Dynamics

The vertical momentum balance of a mine in the sediment phase is given by:

$$M_r dV/dt = F_{w,a} + F_b + F_d + F_c + F_s \quad (6)$$

where  $F_b$  is the buoyancy force in the sediment,  $F_c$  is the compressive force, and  $F_s$  is the shear force.  $F_c$  and  $F_s$  are additional forces (different from air and water phases) exerted on the mine by the sediment. They are proportional to shear strength of the sediment and the projected area of the mine. If the mine is a right circular cylinder, the compressive force is twice the shear force:

$$F_c = 2 F_s, \quad F_s = S_u A \quad (7)$$

The mine burial depth is predicted by integrating (6) with respect to time until the mine velocity becomes zero. Accurate values for sediment properties are essential to the accuracy of this process. Shear strength and density have a strong impact on the computation of all forces as well as buoyancy weight and added mass.

## 6. MODEL-DATA COMPARISON

### A. Model Description

Arnold and Bowen (1980) developed the impact burial model in 1980. In its original form, it modeled the two-dimensional free-fall history of a right cylinder falling through three phases (air, water, sediment) and predicting the final depth of burial in the sediment. While the concept was



accurate, there were a number of problems with the initial model such as a failure to accurately predict terminal velocity in the water column, burial depth in very soft and hard sediments, and unrealistic predictions under some environmental conditions. Recognizing these problems, Satkowiak made a number of modifications to the basic model. These included:

- Correcting the reference flow area used in the drag calculations
- Correcting the calculation of added mass term
- Including a term to calculate the drag due to the front nose of the cylinder
- Allowing for non-blunt noses of mines
- Including an option to input water temperature
- Including the retarding forces in the sediment due to its semi-solid nature

While substantially improving the predictive capability of the model, further improvement were implemented by Hurst. These changes provided new methods for deriving the forces acting on the mine as it passes through the air-water interface and water-sediment interface. The model is extremely user-friendly and allows the ability to input the mine dimensions as long as it is a standard cylinder or tapered mine. User input parameters are listed in Table 2.

TABLE 2. MODEL INPUT PARAMETERS

Mass of the mine in air	Mass of the mine in water
Mine length	Mine diameter
Mine maximum diameter	Center of mass of the mine
Altitude when released	Angle when released
Initial rotation rate	Water depth
Water temperature	Sediment Density
Sediment shear strength	

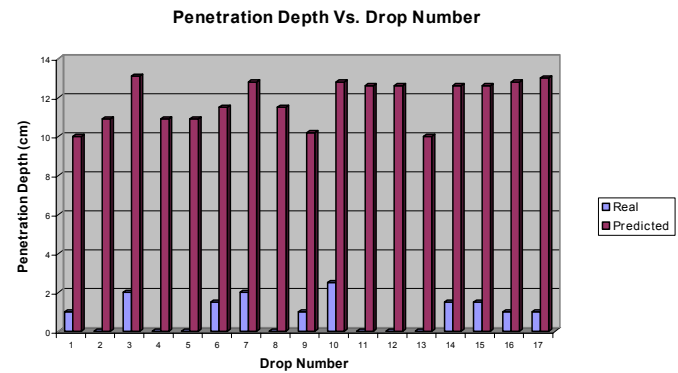


Fig. 9. Comparison between measured and modeled mine burial depths. Here maroon and blue bars indicated modeled and measured values.

### B. Modeled and Observed Burial Depth

After running the model for each gravity core regime and location, the mine burial depths were averaged and compared with measured burial depth data (Figure 9). As evident, the model over predicts actual burial depth by an order of magnitude on average. Since the gravity cores were taken for approximately two to three meters from the impact location, several cores were taken for each drop. This allowed an average to be calculated in order to yield more accurate data. each drop.

## 7. CONCLUSIONS

During the Monterey Bay Mine Impact Burial Experiment, the simulated mines were dropped seventeen times. After each drop, the professional divers measured the water temperature, the mine burial depth and took the gravity cores. Core transportation occurred immediately upon return to the United States Geological Society (USGS). Sediment density and sediment shear strength were analyzed from these cores. This experiment provided a synchronous data set on simulated mine burial and ocean environment. Using this data set to verify the IMPACT25 model, we found that the model consistently over-predicted the mine impact burial at least an order of magnitude.

Parameters inputted into the IMPACT25 model can be broken up into three categories: (1) Oceanographic, which includes water temperature and depth. (2) Physical, which includes release medium, initial velocity, and orientation. (3) Sediment, which includes sediment density and shear strength at varying levels.

It is not believed that there is a problem in how the model interprets the sediment data. Actually, the model is very robust in its ability to allow the user to input multiple sediment layers with varying shear strengths at an impact area.

In addition, although not realistic in a real world environment, sediment data was obtained simultaneously to the drops. A major characteristic of ocean sedimentation is that the layers closest to the surface change frequently due to the dynamic conditions at the water-sediment interface. Should the code ever be run using dated sediment data, results could be immediately held in question due to the significant change that occurs in sediment in relatively short periods of time.

The physical parameters are the most stable factors in the model. Gravitational acceleration is a constant and velocity can be readily ascertained through calculations or direct measurement. There is a forewarned problem with input of how much inertial spin the mine has when it impacts the air-sea interface. This is not an issue as long as the mine is dropped at a fixed orientation, which was the case during the experiment. The code will certainly not correctly calculate the amount of spin or change in orientation experienced by a mine of varying geometry as it strikes the air-sea interface should it be dropped by an airborne platform.

It is the model's lack of sensitivity to hydrodynamic effects in the water column that provides the greatest error. Any water column in an exposed to the open ocean such as Monterey Bay will be subject to variances in wave height caused by tidal and pressure effects. In addition, there will be variances in the momentum flux felt by the column due to current variations in the x, y, and z planes. These effects can cause turbulence in the column that will impede the smooth transition of the mine as it travels from the surface to the bottom. Digital video taken during the experiment illustrated the oscillations of the barrel as it traveled through the water column. These oscillations caused by turbulence act as a frictional force in the water and slow the barrels velocity. Although water density is taken into account by the code, in assuming the water column is a uniformly dense and still medium, overestimation of vertical velocity is predicted. This overestimated downward vertical velocity can affect the codes calculation of impact force and hence, penetration depth.

The essential elements of the mine impact burial model translate into the science and engineering of hydrodynamic process of a falling object and of sediment transport. Any solid object falling through fluid (air and water) should obey two physical principles: (a) momentum balance, and (b) moment balance. The current IMPACT25 model only considers the momentum balance of the mine and disregards the moment balance of the mine. Such an incomplete hydrodynamics in the model leads to unrealistic prediction of the mine falling in the water (no helicoidal motion). If considering momentum and moment balance, the falling object should have a helicoidal motion. Without the helicoidal motion, the IMPACT25 may over-predict the impact burial depth.

Possibilities for error exist in the implementation of the experiment. It was assumed that the barrel was of uniform density because it was filled completely with sand from the

beach. This sand was partially wet and contained small amounts of debris which could minutely affect the uniformity of the mine's density and therefore affect oscillation rate. The divers taking the measurements were using meter sticks and the degree of precision could be called into question. However, errors would most likely not be on a full order of magnitude. Most measurements were made on the order of a few centimeters and the code predicted most penetration depths in excess of 10 centimeters.

In conclusion, use of the IMPACT25 prediction model should be approached with caution. Lack of sensitivity to the hydrodynamic effects in the water column cause the code to predict higher downward vertical velocities and therefore a greater impact force than reality. Since the sensitivity of a mine can be directly attributed to the amount exposed, this error can have dire consequences for the operator in the field.

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